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Transition to Quark Matter and long Gamma Ray Bursts

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Summary. — The energy released by the inner engine of GRBs can originate from structural readjustments inside a compact star. In particular, the formation of deconfined quark matter can liberate enough energy to power the burst. We show that the burning of a neutron star into a quark star likely proceeds as a deflagration and not as a detonation. In that way no strong baryon contamination is produced near the surface of the star. It is tempting to associate the temporal structures observed in the light curves with specific processes taking place inside the compact star. The so-called quiescent times, during which no signal is emitted in the highest energy band, correspond to pauses during the processes of readjustment. If the quark (or hybrid) star formed after these transformations is strongly magnetized and rotates rapidly, a prolonged gamma emission can be produced, as proposed by Usov years ago. This can explain the quasi-plateau observed by Swift in several GRBs.

1. – Introduction

The observations collected by various X-ray satellites and notably by Beppo-SAX and by Swift indicate that the light curve of Gamma-Ray Bursts (GRBs) can be separated roughly in four emission periods, although some of these features can be absent in a specific burst (for a recent review see e.g. [1]).

1) Several bursts present a *precursor*, namely a small signal containing only a tiny fraction of the total energy of the burst, which anticipates the main event by tens or even hundreds of seconds. The duration of the precursor is typically of a few seconds.

2) The main event corresponds to the emission with the highest luminosity and is present in the highest energy band of the emission spectrum. The duration of the main event can vary from few seconds (here we are discussing only long bursts, having durations longer than roughly 2 s) up to hundreds of seconds. As we will show, it is possible to divide the main event into active periods whose duration can be related to the activity of the so-called inner engine, which is the source of the energy of the burst. The active periods are separated by quiescent times.

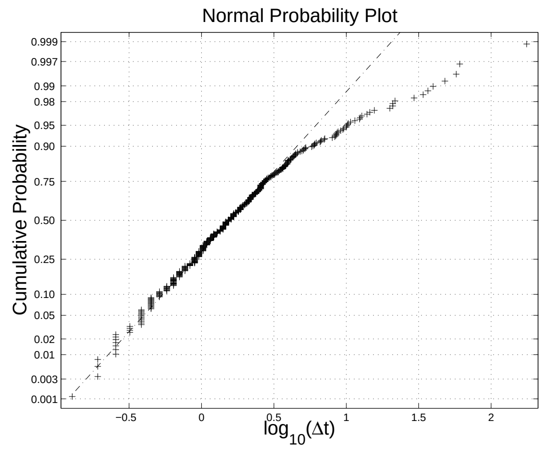

Fig. 1. – Cumulative probability distribution of the time intervals Δt between pulses, compared to a best-fit lognormal distribution. From [2].

3) Swift satellite has recently provided a strong indication that a large fraction of GRBs, after the main event and an initial drop in luminosity, displays a plateau in which the luminosity drops much less rapidly. Inside the plateau some flares can also be present. The luminosity of the plateau is much smaller than that of the main event, but its duration can be much longer, order of thousands of seconds, so that the total energy released can be comparable to the energy released during the main event.

4) At last the luminosity drops steadily and the so-called afterglow begins.

2. – Quiescent times

Nakar and Piran [2] suggested on a statistical basis that the time intervals during which the GRB shows no activity have a different origin than the time intervals separating peaks within an active period. Fig. 1 clearly indicates that the number of long quiescent times exceeds a stochastic log-normal distribution. We have recently investigated the structure of the pre-quiescent and of the post-quiescent emission [3], showing that they share the same micro-structure (see Fig. 2) and also the same emission power and spectral index. Therefore both emissions are generated by a same mechanism which repeats after a quiescent time. It is therefore rather natural to interpret this result as due to different activity periods of the inner engine, during which most of the energy is injected into the fireball. These active periods are separated by quiescent times during which the inner engine remains dormant. The advantage of this interpretation is that it reduces the energy request on the inner engine, the alternative interpretation being that the inner engine remains active and injects energy also during the quiescent times. Moreover, in the latter scenario special conditions on the shells velocity have to be imposed in order to explain why the emission is strongly suppressed although the inner engine remains active. It is possible to show that all GRBs of the BATSE catalog can be explained by assuming two active periods (which in many cases merge and are therefore not distinguishable). After taking into account the cosmological correction on time intervals $t \to t/(1+z)$ with $z \sim 2$ for BATSE, the duration of each active period does not exceed ~ 30 s.

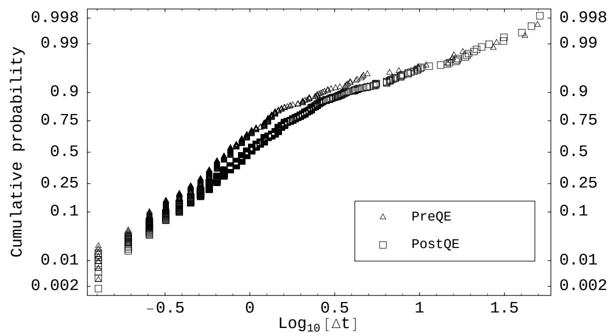

Fig. 2. – Cumulative probability distribution of the time intervals within the Pre-Quiescent and the Post-Quiescent Emission. The two distributions have a high probability to be equal [3].

3. – Hadrons to quarks conversion: detonation or deflagration?

It has been proposed several times that the transition from a star containing only hadrons to a star composed, at least in part, of deconfined quarks can release enough energy to power a GRB [4, 5, 6, 7, 8]. A crucial question concerns the way in which the conversion takes place, either via a detonation or a deflagration. It has been shown in the past that the mechanical wave associated to a detonation would expel a relatively large amount of baryon from the star surface [9]. In the case of a detonation the region in which the electron-photon plasma forms (via neutrino-antineutrino annihilation near the surface of the compact star) would be contaminated by the baryonic load and it would be impossible to accelerate the plasma up to Lorentz factors ≥ 100, needed to explain the GRBs.

We have shown in a recent paper [10] that the process of conversion always takes place through a deflagration and not a detonation. In principle the problem of classifying the conversion process can be solved by comparing the velocity of the conversion front to the velocity of sound in the unburned phase. If the velocity of the front it subsonic the process is a deflagration. The velocity of conversion can be estimated in first approximation through energy-momentum and baryon flux conservations through the front. In Fig. 3 we show the result of such a calculation, indicating that the conversion goes through a deflagration with an unstable front. The instability of the front can be deduced by observing that the velocity of sound in the burned phase is smaller than the velocity of that phase in the front frame. The temperature released in the conversion can also be estimated using the first law of thermodynamics.

The problem of computing the actual conversion velocity is anyway more complicated due to fluidodynamical and convective instabilities. Fluidodynamical instabilities are associated with the possibility of the front to form wrinkles. In this way the surface area increases and the conversion can accelerate respect to the laminar velocity v_{lam} [11]. In the absence of new dimensional scales between the minimal dimension $l_{\min}$ and the maximal dimension $l_{\min}$ of the wrinkle, the effective velocity is given by the expression

$$v_{\rm eff} = v_{\rm lam} \left(\frac{l_{\max}}{l_{\min}} \right)^{D-2} . \quad (1)$$

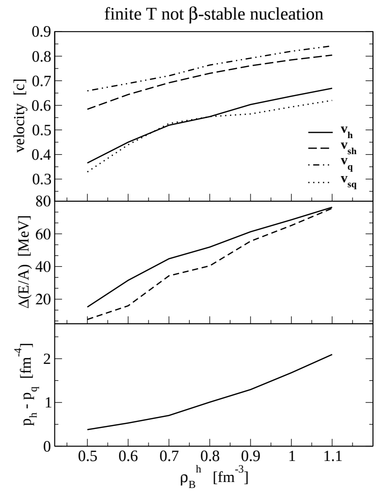

Fig. 3. – Upper panel: velocity of hadronic phase v_h, of the burned phase v_q and corresponding sound velocities v_{sh} and v_{sq}, all in units of the velocity of light and in the front frame. Center panel: energy difference between the two phases (in the hadron phase rest frame). The dashed and the solid lines correspond respectively to the first and to the second iteration in the solution of the fluidodynamics equations. Lower panel: pressure difference between the uncombusted and the combusted phase. Here the combusted phase is obtained using $B^{1/4} = 170$ MeV, temperatures from 5 to 40 MeV (as estimated from the solid line in the central panel) and it is not β-stable.

Here D is the fractal dimension of the surface of the front and it can be estimated as $D = 2 + D_0\gamma^2$, where $D_0 \sim 0.6$ and $\gamma = 1 - \rho_b/\rho_u$. Here ρ_b and ρ_u are the energy densities of the burned and unburned phase, respectively. In this analysis a crucial role is played by neutrino trapping which does not allow the system to reach β-equilibrium on the same timescale of the conversion process. Taking into account this delay of the weak processes, then $\gamma \leq 0.45$ at all densities. The effect of neutrino trapping is displayed in Fig. 4. Our numerical analysis shows that, although the effective velocity can be significantly enhanced respect to the laminar velocity, it is unlikely that $v_{\rm eff}$ exceeds the speed of sound and therefore the process remains a deflagration.

Convective instability can also take place, because in a regime of strong deflagration the energy density of the newly formed phase is smaller than the energy density of the old phase. On the other hand, in a high density system in which relativistic corrections are important the new phase forms at a pressure smaller than the pressure of the old phase (here matter is not yet at equilibrium, which is reached only after a delay). Due to this, when the drop of new phase enters the old phase pushed by the gravitational gradient, its pressure rapidly re-equilibrates and its energy density changes accordingly. Quasi-Ledoux convection develops only if the energy density of the new phase remains smaller than that of the old phase *after* the pressure has equilibrated.

Summarizing, the results of our analysis are the followings:

- the conversion always takes place as a strong deflagration and never as a detonation
- fluidodynamical instabilities are present and they significantly increase the conversion velocity but, in realistic cases, the conversion process does not transform from

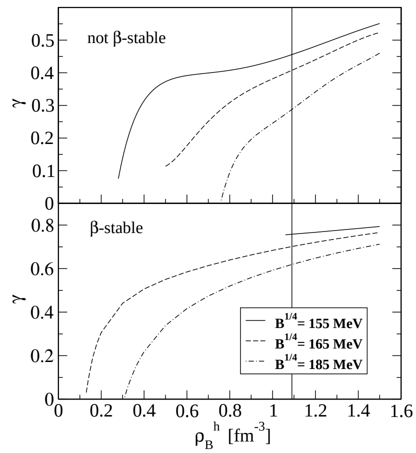

Fig. 4. – The γ-factor entering the fractal dimension of the conversion front. See Sec. 3.

a deflagration to a detonation

- convection can develop in specific cases, in particular it takes place if hyperons are present or if diquark condensate does form.

4. – Structural modifications of the compact star and light curves of the GRBs

We can combine the information provided in the previous sections and formulate a model for the GRBs based on the following scheme:

i) a compact star forms after a Supernova explosion. The explosion can be entirely successful or marginally failed, so that in both cases the mass-mass fallback is moderate (fraction of a solar mass);

ii) after a delay, varying from seconds to years and dependent on the mass of the compact star and on the mass accretion rate, the star starts readjusting its internal structure. The first event could be associated with the formation of kaon condensation (or of hyperons if it goes through a first order transition [12]). This first structural modification could be relatively small, involving only a modification of the central region of the star, but the presence of strangeness can trigger the instability respect to the formation of strange quark matter. The precursors could be due to this process;

iii) the compact star is now metastable respect to the formation of quark matter (if deconfinement at finite density takes place as a first order transition) and after a short delay the formation of deconfined quarks takes place as a deflagration. A hot compact star remains, and it cools-down through neutrino-antineutrino emission. If a quark star forms, photon emission and pair production from its bare surface can have an even larger luminosity [13];

iv) many calculations indicate that Color-Flavor-Locked (CFL) quark matter is the most stable configuration at large density. On the other hand the transition from normal quarks to CFL matter can take place as a first order if the leptonic content of the newly formed normal quark matter phase is not too small [14] (its initial leptonic content equals that of the hadronic compact star). In that way, after a short delay (quiescent time) a second transition can take place inside the compact star, due to the formation of superconducting quarks. Energy is again released, and a hot and more compact stellar object is now formed, which again starts cooling via neutrino and photon emission;

v) the neutrino-antineutrino emitted by the compact star can annihilate near the surface with an efficiency of order percent. Electrons and positrons add to the photons directly emitted. The energy deposited in the electron-positron-gamma plasma can be large enough to power a GRB. The typical duration of the cooling of the compact star is of the order of a few ten seconds. The emissions generated by the various cooling periods of the compact star can explain the main event;

vi) if the newly produced compact star is rapidly rotating and it has a strong magnetic field a non-thermal radiation can be generated by accelerating the electron-positron pairs produced in the magnetosphere [15]. The ultimate source of energy powering this emission is the rotational energy of the compact star and the typical time scale is of the order of hundreds seconds. This emission can explain the plateau observed by Swift;

vii) inside a rapidly rotating compact star, differential rotation can generate toroidal magnetic fields, which can be responsible (via Kluzniak-Ruderman instability [16]) of emission periods continuing long after the violent readjustments of the structure of the compact star [13]. These emissions can explain the re-brightening observed during the quasi-plateau, but could also be responsible for at least a fraction of the main event.

It is interesting to compare the scheme here proposed to the hypernova-collapsar model. In that model the GRB can be associated with a SN explosion which has to be strictly simultaneous with the GRB. In the quark deconfinement model the two events can be temporally separated, with the SN preceding the GRB by a delay which can vary from minutes to years. Arguments in favor of a two-steps mechanism have been discussed in the literature [17].

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Questions

Question Author: C. Fryer.

Question: Can the transition to quark matter take place in the hot, lepton-rich, extended proto-neutron stars that exist ~ 1 s after collapse if the proto-neutron star is approaching high masses?

Answer: It depends crucially on a) the maximum mass of a stable hybrid or quark star, and b) the minimum mass of the compact star at which the transition to quark matter actually takes place. Concerning the first point, it is possible to have stable configurations up to masses of the order of 2 $M_\odot$ (see e.g. M. Alford *et al.*, astro-ph/0606524). Above that limit the star likely collapses to a black hole. Concerning the second point, the minimum mass at which the formation of deconfined quark matter starts taking place is strongly parameters' dependent. Typical numbers range from 1.2 up to 1.5 $M_\odot$ and the large uncertainties are due to our poor knowledge of the equation of state of neutron-rich matter at densities of 2-4 ρ_0. Several scenarios are therefore possible, including the possibility that the transition takes place during fall-back (in the case of a partially failed SN) when, due to mass accretion, the critical mass for quark deconfinement is reached.